

Real-time HEV energy management strategies

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ABSTRACT – Hybrid electric vehicles require an adequate energy management strategy in order to actually optimize their consumption. Many real-time controls were recently proposed in literature, but as each study is performed in a specific context, it is difficult to compare their efficiencies. The present paper proposes a comparison between 3 recent promising real-time strategies: adaptive equivalent consumption minimization strategy (A-ECMS), optimal control law (OCL) and stochastic dynamic programming (SDP). Two off-line methods are used as benchmark: Pontryagin’s minimum principle (PMP) and dynamic programming (DP). Simulation results of a parallel HEV show 5% to 18% fuel economy, compared to a conventional vehicle.

Keywords - hybrid electric vehicle, real-time energy management, optimal control, A-ECMS, OCL, stochastic dynamic programming, Pontryagin minimum principle.

1. INTRODUCTION

Hybrid electric vehicles (HEVs) are widely considered as a promising short-term mean for fuel economy and emission control. However, the fuel saving and CO₂ emissions reduction strongly depend on the energy management strategy used, and finding robust real-time optimization algorithms remains a key challenge.

Energy management strategies studied in the literature can be divided into four groups: rule-based strategies [1] [2], instantaneous optimization of an equivalent fuel consumption [3] [4] [5] [6], global optimization [7] [8] and convex optimization [9]. Each strategy is shown to allow a significant reduction of fuel consumption and claimed to have better performances than others. However, the studies are performed in their own specific context and a horizontal comparison is needed. To this end, the present paper proposes a comparative analysis between three promising real-time strategies, applied to the same parallel HEV, in the same context.

The paper is organized as follows: the HEV model and the strategies to compare are described in Section 2. The simulation results are presented in Section 3 and the parameter setting influence is discussed for each algorithm. Finally, the paper is concluded in Section 4.

2. HEV SYSTEM AND REAL-TIME CONTROL METHODS

The present comparison is performed in the case of a parallel HEV powertrain, because it is supposed to have the best potential for fuel consumption reduction [7]. The purpose of the optimal power management is to search for the best

power split between the internal combustion engine and the electric machine, in order to minimize the fuel consumption over a driving cycle, while meeting the driver’s power demand and maintaining the battery state of charge (SOC).

Three recent real-time strategies proposed in literature were selected, because their authors report excellent performances compared to previous work: adaptive equivalent consumption minimization strategy (A-ECMS) [3], optimal control law (OCL) [6] and stochastic dynamic programming (SDP) [8]. Two off-line methods are used as benchmark: Pontryagin’s minimum principle (PMP) and dynamic programming (DP) [4].

The HEV model and the chosen control strategies will be developed in the full paper.

3. SIMULATION RESULTS AND DISCUSSION

The different strategies were implemented and tested on the WLTC cycle. The setting parameters were determined off-line using the same cycle. It should be noted that authors usually do not give much information about this procedure, although it is an important point for a good implementation.

Table 1 reports the results. The fuel saving is calculated with respect to a conventional vehicle (CV) consumption over the same cycle. DP and PMP have similar performances. However, DP requires much more computation time, which is the main reason why it is often abandoned [10]. Yet, this method remains interesting if one needs to account for SOC limitation [7].

Table 1. Simulation results on the WLTC cycle

Strategy	Fuel consumption (liter per 100km)	Fuel saving (%)	Computation time (s)
PMP	3.48	-18.3	0.1
DP	3.53	-17.1	2
AECMS	3.74	-12.2	0.1
OCL	4.26	0	0.1
SDP	4.26	0	15

As illustrated in Fig.1, the SOC evolution is the same for both off-line strategies. In the meantime, the SOC behavior is quite different from one real-time optimization strategy to another. Since the future driving pattern is not known a priori, the final SOC differs from the initial one. While the A-ECMS tends to keep the battery SOC close to its reference value, the OCL favors battery discharge along the driving cycle and tries to refill it during the final deceleration.

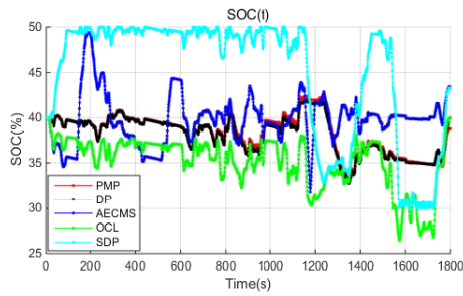


Fig.1 Battery SOC comparison

The A-ECMS strategy tries to adjust an equivalent fuel-cost of electrical power to its optimal value. This optimal equivalent cost depends on the driving cycle and can be obtained off-line using the PMP. Fig. 2 shows this optimal constant equivalent cost and how it is adjusted by the A-ECMS method.

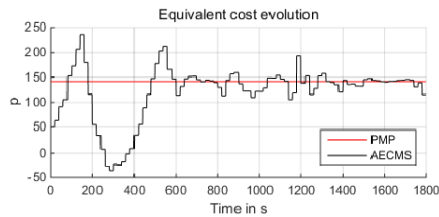


Fig.2 A-ECMS' equivalent cost evolution

According to Tab.1, A-ECMS seems to be the best real-time strategy among the three. However, its performance strongly depends on the set of parameters used. Hence, a series of ten INRETS cycles [11], with different average speed (Tab.2), was used for robustness analysis.

Table 2. INRETS cycles

Type	Urban					Road			Highway	
	UL1	UL2	UF1	UF2	UF3	R1	R2	R3	A1	A2
Average speed (km/h)	4	7	10	19	24	32	41	57	74	95

Fig. 3 shows the fuel saving and the final SOC as a function of the cycle average speed, using the optimal parameters found for the WLTC cycle. It shows that the parameters calculated for the WLTC cycle are not adapted to all INRETS cycle. The method lacks of robustness.

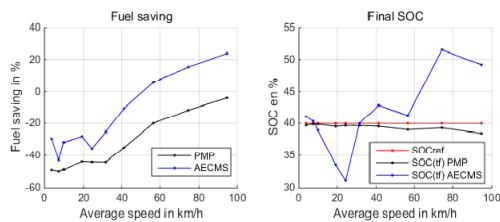


Fig.3 A-ECMS results for INRETS cycles, compared to PMP's

The OCL method [6] was developed to obtain a better robustness than A-ECMS. According to the author, it gives a solution close to the optimal one and is stable enough to work for any driving cycle with one single parameter, denoted μ . However, by testing different INRETS cycles, the robustness analysis of the OCL method shows that OCL fails to decrease the fuel consumption and insure charge sustaining at the same time (Fig.4). A parameter specific to each type of driving conditions (urban, road and highway) may help to improve the results.

The SDP, a proven method in other area, uses statistics to model the driver's future power demand and calculates an

average optimal solution. The implementation proposed in [8] was tested and shows poor results. While PMP saves 18% of fuel over the WLTC cycle, SDP performs like a VC (Tab.2). However, the method proposed in [8] relies on a simplified powertrain model. If the same simplification is applied to the classical vehicle and to PMP, then SDP performs almost as well as PMP (5% fuel saving, instead of 6%). We are currently investigating this point. It should be noted that the SDP performance relies on an adequate probability distribution of the vehicle's driving speed, which requires a large amount of data not always available. This can be seen as a drawback or on the contrary as a way to include more information about the current trip of the vehicle.

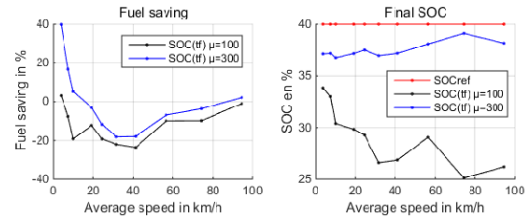


Fig.4 OCL results for INRETS cycles, for two different values of the setting parameter of the method

4. CONCLUSIONS

Three promising real-time strategies from the literature have been selected and implemented. The simulation results show that A-ECMS performances are largely affected by the setting parameters. OCL method, with only one parameter to adjust, is much more robust than A-ECMS, but it can not guarantee fuel economy. We are still working on the SDP to improve our analysis. The full paper will give more details about the HEV model and the strategies which are compared. More results involving more cycles will also be given.

5. REFERENCES

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